Fracture and Gully Formation in Glacial Fill: Field Observations at the WillowCreek Landfill, Portage County, Ohio, with Implications to Historic Earthen Dam Failure Sites in the US[1]

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ABSTRACT: Fracture formation in fill was observed to occur rapidly, in just a few years at the WillowCreek Landfill site. The soil science and geomorphology literature does not discuss the formation of fractures in glacial fill. Observations (which are often the first step in developing a research effort) of fractures formed in fill derived from fine-grained Ohio glacial soils and tills by Weatherington-Rice at the WillowCreek site and in earthen dams by Sherard are here presented. Questions regarding the applications of these observations to potential impacts and failures of the built environment, that is, landfill construction and leachate generation (HELP model), earthen dams, highway construction, and general construction sites, are raised. Recommendations are made for the need for inter-disciplinary research and literature sharing.

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INTRODUCTION

Fractures in *in situ* fine-grained glacial materials have been discussed at length in a number of publications, some dating more than 100 years back (Read 1880; Gilbert 1882; White 1982; Weatherington-Rice and others 2000; Brockman and Szabo 2000; Haefner 2000). A partial listing of these papers can be located at http://www.oardc.ohio-state.edu/fractures.

Both of the authors have noted the formation of gullies at fracture locations in *in situ* materials in Ohio. This topic has also been discussed at field days and conferences, notably at the field trip for the 1994 Geological Society of America Penrose Conference on Fractured Tills in Racine, WI. However, the soil science and geomorphology literature is silent on the relationships of gully formation to pre-existing vertical fracture formations in soils or fill.

The geologic field contains an extensive body of literature that addresses the formation of gullies and streams at jointed and fractured points in bedrock lithologies. For example, Hills' 2nd Edition (1972) of *Elements of Structural Geology* provides a comprehensive summary of the topic. Hills references Hobbs' (1911) discussion on the tracing of long regular, repeating structures. By the earlier 1911 publication date, Hobbs had already assigned the term "lineament" to these structural features.

Lineament mapping or fracture trace analysis of regional jointing patterns from aerial photography or LANDSAT remote sensing overflights has long been a geological practice when searching for structural instabilities and/or hydraulically active locations for the installation of bedrock ground water wells. The Edward E. Johnson Company, manufacturers of well screens, in their very first edition of *Ground Water and Wells* (1966), includes photographs of fractured limestone rock when discussing water-bearing capacities of lithified bedrock aquifers. Fracture trace and lineament analyses in bedrock are typically taught in upper level undergraduate geomorphology, structural geology, and hydrogeology classes as a laboratory exercise or as a geologic field camp problem.

A small body of literature that relates to the behavior of *in situ* fractured materials from a geotechnical standpoint does exist. Allred (2000), referencing publications that date back to the 1960s and 1970s such as Duncan and Dunlop (1969) and Lo (1970), indicates that fracturing may have a significant impact on the physical consolidation and shear strength of materials in geotechnical and construction foundation applications. Allred notes in his summary that, "Settlement occurs at a faster rate when fractures are present. If fractures are open, a modest increase in total settlement is possible." Additionally, when discussing shear strength, he notes, "Glacial till fractures decrease overall shear strength. After excavations or erosion of surface material, stress release and water infiltration lead to further reductions in overall shear strength."

Allred has limited his discussion to the "cut" portion of the typical "cut and fill" setting common to modern construction in glaciated Ohio and eastern North America. His paper did not discuss the function of fracture formation in fine-grained glacial materials used as construction fill. Sherard and others (1963), in their treatise *Earth and Earth-Rock Dams*, come tantalizingly close to making the connections between fracture formations and fill materials. They note, in reference to surface cracking in arid southwestern locations, that "homogeneous dams of very fine clayey silt and silty clay of low plasticity have been so badly eroded with concentrated gullies, starting in drying cracks, that they have had to be almost completely reconstructed."

Because such fill materials are derived from a multitude of locations, the behavior of fill at site-specific locations will vary. However, it is possible to make some general predictions by applying the generalized information that has been collected in both the first

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Special Issue of *The Ohio Journal of Science* on “Fractures in Ohio's Glacial Tills and in this issue. By applying information gleaned from the first issue papers of Brockman and Szabo (2000), Tornes and others (2000), Fausey and others (2000), and the detailed grain-size information presented in Szabo (2006) and Kim and Christy (2006), it is possible to extrapolate field observations made at one location to potential geomorphologic, geotechnical, and soils behavior at other locations where similar materials have been used for construction “fill.” It is also possible to extrapolate these field observations to other construction applications such as the construction of a “clay” cap over a landfill or a contamination clean-up location. This paper documents field observations made over a several years' fieldwork and drilling efforts, during the early and mid-1990s, at the WillowCreek Landfill, Portage County, OH (Fig. 1).

Figure 1. Location of the WillowCreek Landfill, Portage County, OH.

The WillowCreek Landfill is located in the old Petersen coal strip mine (Weatherington-Rice and others 2006). The site can be located on Figure 1. Residual material remaining at the site is strip mine spoil, predominantly solidified fractured and weathered bedrock that is derived from Pennsylvanian-aged sandstones, siltstones, claystones, shales, and limestone, which were stripped and discarded as part of the coal mining process. Most of this material is not suitable for the construction of landfill liners, cover, or caps. Materials for these applications require a fine-grained material that allows at least 50%, by weight, to pass through a 200-mesh (0.075 mm) sieve.

This requirement for 50% of the materials passing the 200 mesh sieve has been developed by the United States Environmental Protection Agency (US EPA) using the Unified Soil Classification System (USCS, supported by the American Society for Testing and Materials), which characterizes all materials passing through the 200-mesh sieve as “fines, including both silt- and clay-sized materials. The clay minerals component of the materials is not determined. The American Association of State Highway and Transportation Officers (AASHTO) uses this break point as the geotechnical separation point between fine sand and silt-sized particles, again with no mineralogy attached (Ward and Trimble 2004).

In an attempt to locate enough fine-grained material for clay liners, daily, intermediate, and final cover at the landfill, the owners of the WillowCreek Landfill developed a program to construct farm ponds and lakes for local residents. These ponds and lakes were built, free of charge, in return for the removed fine-grained spoil material that could be used at the landfill facility. The landfill operators also took fill from foundation excavations. This fill, a mixture of predominantly Hiram and Kent tills (Winslow and White 1966; Delong and White 1963) and the resulting soils formed on those glacial deposits, were stockpiled in an unsorted manner at the WillowCreek Landfill.

Most of the fill was dumped on the northern portion of the landfill in a large staging area that ranged up to 20 m in height in some sections and extended over several acres. After one truckload/lift was placed over the stockpile area, additional dump trucks would add additional lifts, driving over the lower emplacements, providing for a limited compaction process, not unlike a typical “fill” process at any construction site. Since the material was continually being used at the landfill, the material at the main stockpile was moved on a regular basis to other points on the landfill, remaining in place for no more than a few years before it was again transported to another location on the site. To assure compliance with the 50% 200-mesh sieve (0.075 mm) size requirement, the original stockpiled material was reworked, screened, and moved by conveyor to secondary stockpile areas for final emplacement on the site. No attempt was made to segregate Hiram from Kent tills or weathered soil materials from unweathered glacial till materials. Typical grain sizes for these materials can be found in Winslow and White (1966), Delong and White (1963), Szabo (2006), and in the Soil Survey of Portage County, OH (Ritchie and others 1978) and the Soil Survey of Stark County, OH (Christman and others 1971).

MATERIALS AND METHODS

The first author of this paper conducted a geologic and hydrogeologic investigation at the WillowCreek Landfill site in Portage County for over two years in all typical seasonal weather conditions. An extensive series of photographs were taken as part of the site investigation and monitoring-well installation drilling project at the WillowCreek Landfill in Portage County. The photographs included a series on the clay stockpiles, the existing conditions of the pre-Resource Conservation and Recovery Act (RCRA) clay caps, and installation of the RCRA clay cap over the main landfill sections. These photographs document fill locations and landfill final cap cover materials that had been in place for less than five years at the time of the photographs. Field notes were checked to verify the sources of the fill materials.

RESULTS

During the field activities, the pre-RCRA clay caps were observed during all seasons of the year. The clay caps were measured to be deeply fractured from the surface down to at least 0.5 m below ground surface. During rain events, precipitation was observed flowing into the fractures in the cap. During winter snow-covered frozen-ground conditions, snow melted away from the active fractures and small cone-shaped mounds were created as warm landfill gas migrating out of the landfill carried a water and fine-grained soil mud mixture out of the landfill. The gas, mostly methane but also containing odorous organic acids, could be smelled as it rose into the air. The extruded water and soil mud mixture froze at fracture sites across the pre-RCRA-capped areas, creating a bumpy landscape resembling miniature volcano cones.

At two locations, the glacial materials stockpiles had to be benched to create a stable drilling surface for the monitoring well installation process. The benching activity created fresh-faced vertical cuts into the stockpiled glacial materials. Both stockpiles were relatively new, no more than several years in age at the benched locations. They had both been through at least one winter period, however, so they were subjected to both at least one freeze-thaw cycle and at least one hot-summer desiccation cycle. Since these materials are not typically rated as part of *in situ* regional evaluations, such as the county soil survey or the county level DRASTIC evaluations, limitations such as these observed are seldom noted in the common county level references.

The photographs taken of these stockpiles during the several years of field activity on the site document extensive fractures and gullies that had been formed in a very short period of time. Figures 2 through 4 document the newly formed fractures in the fill material. Figure 2 shows the fill at the initial staging area where glacial tills and their associated soils had been stockpiled for approximately five years or less. This photograph was taken at the top of the first staging pile, which rose to a high point of 20 m above the surrounding ground surface. This upper portion represents only one to two years of placement of fill. Figure 3 shows the fill after being pre-sorted at the northwest pod location where the stockpile had been in place for only two years. Figure 4 shows the fill used as a pre-RCRA final cap, at this location the cap had been in place for approximately five years. Additional photographs from this site can be seen in Chapter 2 of Weatherington-Rice (2003).

In each case, the fractures formed rapidly. The vertical fractures appear to control the surface representation of gully formation in Figure 3. There are vertical fractures with surface gully formations on top of them. There are also vertical fractures between the gully formations, but there are no gullies without vertical fractures formed underneath them. These relationships were documented in one field setting at the WillowCreek Landfill, but it has been the experience of the authors, upon reflection, that these observations have been made by them at other construction sites and agricultural field locations around Ohio. The ability to view and photographically document the process in three dimensions is the unusual contribution from this field experience at WillowCreek.

FIGURE 2. Vertical fractures in top dump lifts, initial staging area. Note fractures appear to form across variations in texture and color within the stockpiled deposit. Cut approximately 2.0 m high. These newly formed fracture faces are not stained and/or do not have secondary mineral depositions. (Photo by J Weatherington-Rice)

This relationship of fractures to gullies is not unlike the conditions on earthen dams noted in the southwest by Sherard and others (1963). As witnessed in the field, the fractures also contribute significantly to the migration of precipitation infiltration into the landfill and gas migration out of the underlying solid waste materials at the site (Fig. 4). This observation has been confirmed both visually and by smell.

Cut and Fill, Landfill Caps

Fractures of the nature observed at WillowCreek may have a considerable impact on the ability of water to move through the fill materials, the consolidation of the materials, and the initial and final shear strength of the fill materials as discussed in Allred (2000). This mechanism could be the underlying failure mechanism that controls foundation cracking and failures at new construction sites, especially in poured slab foundations. These fractures also would have acted as contaminant

FIGURE 3. Close-up of the northwest pod stockpile. Cut side can be seen in the larger scale photo. Note the vertical fracture supporting the gully formation in the center of the picture. Cut face approximately 1.5 m high. (Photo by J Weatherington-Rice)

transport routes at WillowCreek if the northwest pod landfill cell had been constructed on top of 15 feet of this fill material as previously envisioned by the property owners.

The final landfill cap in place at this pictured location was installed before 1990 (Fig. 4). Therefore, there was no synthetic Resource Conservation and Recovery Act (RCRA, 40 CFR Parts 240-299) cap installed under the final soil and vegetative cap to prevent inflow of precipitation or the escape of landfill gases from the site. Much of the existing landfill was undergoing final closure under RCRA requirements but there were old sections as well, such as the area shown in Figure 4, which closed before RCRA was passed, so those sections remain without a synthetic underliner to the cap.

With this level of fracture failure allowing infiltration of precipitation through the cap, it is not difficult to understand why many pre-RCRA capped landfills in Ohio are generating more leachate than was predicted through the use of the Hydrologic Evaluation of Landfill Performance (HELP) model (Env Lab USACE 1997). The HELP model is a nationally accepted engineering model used to predict, among other management considerations, the volume of leachate to be generated from a closed landfill over time. The HELP model does not take into consideration the fractured nature of Ohio's glacially derived soils and capping materials and calculates recharge through the primary matrix permeability of the materials as established by samples taken from the landfill's test pad before it fractures.

Dams as Well?

Sherard and others (1963) conducted an extensive engineering and geotechnical analysis of the types of failures in earthen and earth-rock dams worldwide from approximately 1850 to 1960. They identified the three most common causes of catastrophic dam failure to be floodwaters overtopping and destroying the dams, piping, "and earth slides in the downstream portions of the embankment or foundation." They come tantalizingly close to making a connection between several types of failure, that is, piping, differential settlement cracking (also discussed more generally by Allred [2000]), embankment and foundation slides, downstream slope

FIGURE 4. Linear- and polygonal-controlled fractures on final cap, pre-RCRA section WillowCreek Landfill. Note vegetation mostly restricted to matrix areas. Gas migration through the fractures contributes to lack of vegetative cover on the cap's surface. Cap approximately five years old at this location when photographed. Fractures were traced at least 0.5 m through the cap material by inserting a stiff survey flag wire shaft until resistance was reached. (Photo by J Weatherington-Rice)

slides, and damage due to surface drying. It is only in the section on surface drying that they make the connection to gully formations noted above. Sherard and others (1963) note:

> "If the construction surface of an embankment of fine-grained soil is allowed to dry in the sun, drying cracks can greatly increase the overall permeability of the materials. This has happened even on dams constructed in accordance with good modern practice."

It is exactly this desiccation phenomenon, coupled with freeze-thaw, which caused the failure of the landfill clay cap shown in Figure 4. While the initial landfill cap construction may have occurred at optimum moisture content, one annual Ohio cycle of freeze-thaw and summer drying is enough to begin to breach the emplaced clay cap. The deeply fractured pre-RCRA clay cap at WillowCreek (Fig. 4) was less than five years old when photographed.

The connections to the underlying fracturing mechanism and the relation to differential settlement cracks, embankment and foundation slides, and downstream slope slides are less clearly made by Sherard and others (1963). Their work appears to be more involved in categorizing how the dams failed, rather than what phenomenon controlled the initial fracture formations which resulted in either water moving through the dam (piping) or the dam being removed (sliding). They do, however, make two extremely important observations. Regarding slides, they note that:

> "Almost all slides during construction and all deep upstream and downstream slides after construction have occurred in dams underlain by foundations of clay relatively high in plasticity and natural water content. In addition, a strong correlation exists between the incidence of slides and the use of fine-grained and highly plastic soil in the embankment."

From these comments, it is possible to extrapolate that the higher the saturation of the materials, and the more plastic the clays, the higher the probability that failure will occur "en masse" as opposed to through piping, and that the materials of the dam themselves actually move.

The link to interior cracking is less clear than the link to the "en masse" movement. Sherard and others reference Sherard (1953) in a study of 17 dams that either cracked or were subjected to large strains without cracking. From this study they note:

> "Although the evidence on which this study was based was sketchy, it indicates that embankments of inorganic clays of low to medium plasticity (plasticity index less than 15) with gradation curves falling within the range shown in (*their*) Fig. 2.3:6 are probably more susceptible to cracking when compacted dry than either finer or coarser materials. It also shows that clays of higher plasticity (plasticity index more than 20) which are finer than the gradation range in (*their*) Fig. 2.3:6 will withstand much larger deformations without cracking."

From these two quotations, it is possible to draw the conclusion that wetter materials are more prone to slides and drier materials are more prone to cracks. In addition, with the range of gradation of soils suspected to crack, shown in their figure, a soils researcher has a qualitative range of conditions identified that could be used as the basis for a study of a continuing relation between what appears to be the two end points of dry cracking and wet "en masse" sliding.

The next link to dam failure caused by piping is less well documented in Sherard and others (1963). They acknowledge that there may be a variety of construction errors and material limitations that set up the physical conditions that result in piping. They do note, however, that, "Embankment leaks through differential settlement cracks have also been a major source of trouble." And further "animal burrows and drying cracks have sometimes caused difficulty." They reference Sherard (1959) whose study of piping leaks in 31 dams noted "the embankment soil properties and particularly the plasticity of the fines, had a larger influence on piping resistance than the method by which the embankment had been compacted." This study further notes that:

> "Laboratory research is urgently needed to extend knowledge concerning the influence of soil types (*that is, earth materials in the engineering sense – italics comment added for clarity*) and density on piping resistance of compacted soils."

Later, Sherard and others (1963) note, "Current lack of knowledge on this point is a ridiculous anachronism considering the general advance of modern soil mechanics and the great need for the information." If this research has since been completed, the authors of this paper, trained in geomorphology and soil science, have found no trace of it in the geotechnical literature.

Finally Sherard and others (1963) do make a conjecture between piping and cracking. They note that:

> "While the danger of cracking has not been widely publicized or understood by earth dam engineers, it is possible that a large number of leaks which have led to piping failures have originated from embankment cracks than from any other sources. Although many of these failures have been in small and cheaply constructed dams, a considerable number of large well-constructed dams have developed alarming cracks in recent years."

They then identify two reasons for the lack of attention to this issue of cracking. The first is the reticence on the part of dam engineers or owners to acknowledge these defects in dam structures. Their second reason is one of lack of definitive information as they state that, "cracking in earth dams has not received the consideration it deserves…the true cause of failure often has not been identified." Often there is no one present to notice that piping begins from embankment cracks or the cracks simply are hidden within the dam and may never have been visible. This lack of documented field observation is a critical missing link in understanding the root mechanisms of piping failure in dams.

DISCUSSION

Fractures form very quickly in a fill environment where fine-grained glacial materials are used for the bulk of the fill and/or cover material. This fracture formation process is a controlling factor in the formation of surface gullies in fill and possibly in *in situ* soils. In addition, the fracturing quickly controls the surface to groundwater transport system in the built environment. These observations open a number of questions that have direct bearing on the health and safety of all Ohioans.

Of the more than 50,000 dams in Ohio, the State of Ohio currently (August 2005) has 2,694 dams registered with the Ohio Department of Natural Resources – Division of Water (ODNR-DOW 2005). These include 499 Class I dams (which include most, if not all of the Army Corps of Engineers (ACOE) flood control dams in the state), 539 Class II dams and 704 Class III dams. All of these dams with the exception of the ACOE dams fall under ODNR-DOW jurisdiction for inspection (ODNR-DOW 2005). Just several years ago, the Class I dam (failure would result in probable downstream loss of life and property destruction) at Lake Seneca in Williams County began to fail by piping and the lake had to be drained quickly for the dam repair. Fortunately, the failure was discovered before downstream damages were incurred.

Included in that total number of dams, under the guidance of the USDA Natural Resources Conservation Service (NRCS), several hundreds of dams have been constructed in Ohio using the NRCS specifications. Many of these are small farm pond embankments but they also include approximately 77 smaller watershed flooding project dams completed under the Federal Public Law 566 Program or the earlier demonstration projects, such as the Upper Hocking River – Hunter's Run project in Fairfield County (Stafford 2003).

In addition, Ohio is home to hundreds of old landfills and dumps, which were closed and/or abandoned with pre-RCRA caps and/or simple soil covering. The original inventory of old dumpsites was conducted in the 1960s by local health departments. Some of those records still exist at the county level but many of them are lost. The actual number of old and/or abandoned sites is currently unknown by the Ohio Environmental Protection Agency (Ohio EPA) or any other central data collecting agency. A comprehensive master list is not kept. Searches of the Ohio EPA web site found references for closed historic sites by District attached to yearly Ohio EPA activity reports, but no summary document. For instance, the 2003 Annual Report referenced the clean up of 25 open dumps and scrap tire sites in the Southeast District (Ohio EPA 2003). An in-house search by the Chief of Division of Solid and Infectious Waste, Dan Harris in August 2005 unearthed one historic Ohio EPA Inter-Office Communication dated 17 May 1984 (Speakman 1984) that listed 54 known sites in the Northeast District area at that point in time. Discussions with and searches by staff at the Ohio Environmental Council and Ohio Citizen Action failed to unearth any other historical listings of abandoned sites. It must be remembered, however, that both of these organizations suffered a destructive fire at their shared Columbus, OH, headquarters building in 1987 that destroyed much of their historic repositories.

The Ohio State University Extension has taken a proactive approach to addressing the issue of abandoned dumps and their clean-up issues. Their Extension FactSheet, "Abandoned Dumps: Yesterday and Tomorrow" (Hughes and others 2005), discusses the processes used to evaluate and remediate old facilities and lists reporting locations for each of Ohio EPA's five districts. As Ohio's geologic materials demonstrate that they are lacking in long-term protection abilities, Ohioans find themselves counting on the synthetic, engineered portions of the RCRA caps to insure that precipitation does not enter current RCRA-designed dry entombment solid and hazardous waste landfills. As of this writing, only clay caps are required on construction and demolition debris landfills.

In addition, Ohioans travel across the state on major highways and interstates. These major roadways, designed to minimize grades and curves, rely significantly on the use of cut and fill construction practices, especially in the more rolling portions of the state. Everywhere in the state, construction from the smallest bungalows to the largest high-rises and shopping centers rely on the basic practices of cut and fill to provide flat and stable building sites.

Traditionally the field of geotechnical engineering has been more concerned with the sizes of earth materials than the actual chemical and physical properties of Ohio's soils and underlying geologic materials. As has been seen in earlier works (Brockman and Szabo 2000; Fausey and others 2000; Szabo 2006; Kim and Christy 2006), not all of Ohio's earth materials behave the same way, based solely on their grain sizes.

Research Needs

The references cited and observations documented in this paper open up a number of avenues for further research by soil scientists, engineers, and geologists. Such avenues include investigations into the relation between fracture formation in fill and compression and slope stability. Is the traditional practice of placing fill at an optimum moisture level in six-inch lifts and compacted with equipment such as a sheep's-foot roller actually undermined by the post-construction formation of fractures in the fill material? Could this process of post-construction fracturing be a possible cause of dam failures and highway construction slope failures? In construction sites where less stringent compaction measures are required, could this fracturing process be a controlling factor behind the settlement cracking in house and driveway foundations, especially where they are constructed over fill?

Are the vertical fractures-to-surface gully relations a controlling factor in the location of drainage ways in *in situ* settings? Could the surface geometry of surface water flow to rill collection to gully formation actually be mirroring the subsurface geometry of soil formation? Are the polygonal pedogenic fractures of soil formation partly controlled by the more regional linear fracture directions? If so, would it be possible to model subsurface fracturing systems by studying the rill to gully formations on the surface of the ground?

It has long been thought that slope is a controlling feature for rill to gully formation. Could slope also somehow be a controlling factor to subsurface fracture formation? Where observed in cross section by the authors, all gullies appear to have underlying vertical fractures but not all vertical fractures are capped by gullies. Is there a relation between these formations that is linked to slope, grain size and clay mineralogies?

As mentioned before, with the advent of RCRA caps at solid and hazardous waste landfills, the failure of the clay caps as seen on the older portions of the WillowCreek Landfill will be minimized, at least until the underlying synthetic capping materials fail. However, sections of landfills which use daily and intermediate cover of Ohio's glacial materials will not have the protection of the less pervious synthetic materials to reduce the levels of infiltration until final cover is achieved.

Ohio's landfills are typically found to generate more leachate than had been predicted by their designers and their regulators. Is there a need to modify the HELP model to take into consideration the double block or dual porosity that forms in many of the eastern North American glacial materials when compacted? Does the commercial clay "bentonite" swell quickly enough to prevent additional infiltration in those settings? Would it be more realistic to develop a series of HELP models that could be designed and fine-tuned to the physical and chemical properties of the fine-grained materials being used in different parts of the United States? Should leachate collection and handling system designs be modified to successfully manage the additional leachate generated?

Finally, is it possible to modify the fine-grained materials themselves? Can the addition of organic materials, polymers, or expanders help to stabilize the fracturing mechanism that occurs when fine-grained materials are wetted and compacted to optimum conditions. As we have seen at the WillowCreek site, Ohio fine-grained material, when tested with equipment such as double ring infiltrometers, pass the required hydraulic conductivity benchmarks, simply to later dry out and crack after installation. Are the engineers and designers expecting more from fine-grained materials than the materials are able to give in an unaltered state? If the materials must be altered, are there cost effective, environmentally friendly, non-toxic materials, and methods that can be used to achieve those alterations?

Clearly, the lists of questions that have been triggered by these observations are extensive. This summary includes only the most obvious ones. As has been seen in so many of the other activities of the Ohio Fracture Flow Working Group (OFFWG 2001), while these applications may be most commonly used in the fields of civil and geotechnical engineering, the solutions to these questions may be found in the domain of soil scientists, geologists, and agricultural engineers. Bridging these communication gaps and encouraging interaction between multiple disciplines is critical on all levels, from familiarization with the literature of all of the fields to research oriented teaming for needed problem solving.

SUMMARY & CONCLUSIONS

Three major conclusions can be drawn from the information presented in this paper. Fractures form rapidly and deeply in construction fill settings formed from Ohio's fine-grained glacially related materials. This process has been documented by field observations over several years time at the WillowCreek Landfill in Portage County, OH.

Based in part on these observations, a new research project has begun which hopes to determine the grain-size boundaries and clay mineralogies that control fracture formation. One of the goals of this project is to better quantify the fracturing process. Preliminary results are presented in Kim and Christy (2006).

Numerous fracture observations made by members of the Ohio Fracture Flow Working Group documented in this 2nd Special Issue of *The Ohio Journal of Science* and elsewhere, demonstrate the ubiquitous nature of fracturing in *in situ* settings. The fill setting at WillowCreek extends the limitation of fracture formation to the built environment. This linkage between observed fractures and potential failure in the built environment such as piping in dams and fractures in the clay caps of landfills needs further research to prevent potentially life-threatening site failures in the future.

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